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The characteristics of chromium-sensitized solid state lasers operating in the mid-infrared wavelength region have been studied. During the second year of research there was continued work on crystals doped with holmium and erbium, operating in the 2100-nm and 2800-nm regions. In addition, preliminary measurements were made on the laser performance of thulium around 2010 nm. For all these materials the effect of pump pulse length on output energy and overall efficiency has been measured. A flashlamp-pumped Cr,Nd:GSGG slab laser was operated and characterized at 1061 and 1310 nm. Measurements included comparison of normal mode slope efficiencies, input-output vs. pump pulse length, characterization of thermal lensing and measurement of Q-switched performance at 1061 nm. Spectroscopic properties of GGG crystals doped with Cr4+ ions were measured, including absorption and emission spectra and fluorescence lifetime.

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# Chromium Sensitized Garnets for Mid-IR Lasers

Final
~~Annual~~ Technical Report, 1989-90

**Contractor:**

**Schwartz Electro-Optics, Inc.**

**Research Division**

**45 Winthrop Street**

**Concord, Massachusetts 01742**

**Sponsor:**

**Air Force Office of Scientific Research**

**Contract F49620-88-C-0046**

# 1 Statement of Work

The original statement of work for the contract is as follows:

Study the spectroscopic properties related to infrared laser performance of chromium sensitized garnet crystals, including Er,Cr:YSGG, Ho,Tm,Cr:YSGG, Er,Yb,Cr:YSGG, Er,Yb,Cr:YSAG and Tm,Cr:YSGG. Study the laser properties and performance characteristics of the most promising of these doped crystals. Studies conducted shall include, but not be limited to:

a. Specify and procure appropriate samples of the multiply doped garnet crystals.

b. Measure, for each of the obtained crystals, the absorption and emission spectra, fluorescence excitation spectra, and lifetimes involved in potential laser transitions.

c. Determine energy-level interactions and rates of energy transfer between rare earth ions in the crystals studied.

d. Study laser operation with flashlamp pumping. If lasing is obtained, measure laser characteristics including threshold, slope efficiency, wavelength, insertion loss and thermal lensing in the host medium.

e. Evaluate the suitability of laser materials and measurements for Phase III development.

# 2 Status of the Research Effort

The second year of research included investigations in the following areas:

1. Continuation of studies on the 2.1-μm laser characteristics of flashlamp-pumped Cr,Tm,Ho:YAG, including energy output vs. input energy with pump pulse length as a parameter.

2. Investigations of the laser characteristics of 2.8-2.9-μm Er-doped crystals, including measurements on the temporal characteristics of Cr,Tm,Er:YSGG as a function of pump pulse length and a comparison of Er:YAG and Cr,Er:YAG laser crystals.

3. Preliminary measurements on the laser performance of 2.01-μm Cr,Tm:YAG systems.

4. Operation and characterization of a flashlamp-pumped Cr,Nd:GSGG slab laser, including comparison of normal-mode slope efficiencies at operating wavelengths of 1.06 and 1.31 μm, measurements of input-output energy vs. pump pulse length, characterization of thermal lensing in the slab as a function of pump average power and measurements on the performance of a Q-switched, 1.06-μm system.

5. Spectroscopic measurements on GGG crystals doped with $Cr^{4+}$ ions, including absorption and emission spectra and fluorescence lifetime.

Each of the areas is discussed in more detail below. Most of the discussion is in summary form, with a full description reserved for the Final report.

## 2.1 General

Before discussion of our laser measurements, we note that a new flashlamp driver, developed primarily with the support of another program, was constructed for use in our research into Cr-sensitized lasers. Conventional lamp drivers employ LC discharge networks to generate the drive for flashlamps. The width and shape of the pulse are complex functions of the flashlamp bore diameter, arc length, gas and gas fill pressure, the values of the discharge capacitance (C) and inductance (L) and the charging voltage [1]. Changing the pulsewidth typically requires that both the L and C values be changed, a tedious and expensive procedure if wishes to change the pulsewidth by, say, a factor of 10.

We developed a new driver system for flashlamps based on the use of a Darlington power transistor to switch voltage on and off into the lamp. Transistors of the voltage and current rating (>1000 V and 1000 A, respectively) needed for the application have recently become available. Our driver circuit also employs a bank of electrolytic capacitors to act as a storage element, in conjunction with a capacitor charging supply. Unlike the conventional LC discharge networks, the capacitor bank is used to maintain nearly constant voltage across the lamp during the lamp pulse. The driver thus supplies a nearly rectangular pulse to the lamp, and the pulsewidth is easily controlled by controlling the width of the electrical pulse into the Darlington transistor. Our driver system allowed us to vary the pulsewidth of the lamp from below 100 μsec to beyond 2 msec.

As noted in the Annual Technical Report for 1988-89, our experimental apparatus for laser measurements was based on our commercial flashlamp-pumped laser system, the ***Laser 1-2-3***. Our conventional pump cavity for the laser rods uses a single-flashlamp, silvered-ellipse design. We also developed a cavity based on the use of Spectralon as a diffuse reflector; Spectralon is a thermoplastic resin developed by Labsphere (North Sutton, NH) and has a spectral reflectance of <95% over the 250-2500-nm wavelength region. We worked with Labsphere in developing Spectralon reflectors for our pump cavities, and some of the laser data compares the performance of systems with silver imaging and Spectralon diffuse pump cavities. The advantage of a diffuse pumping cavity is a generally more uniform distribution of pump energy throughout the laser rod compared to the an imaging cavity.

## 2.2 Holmium-doped lasers

Holmium (Ho)-doped lasers operating in the 2.1-μm wavelength region are of interest as eye-safe sources for laser radar systems, pumps for infrared parametric oscillators and as sources for fiber-delivered laser-surgery systems. Much of the early work on Ho lasers, extending back two decades, involved operation of the laser with cryogenic cooling of the crystal, in order to

reduce the lower-laser-level population and improve the process of sensitization of the Ho ion by other rare earths such as thulium (Tm) and erbium (Er). With the demonstration of efficient room-temperature chromium (Cr) sensitization of Th in some host crystals [2,3] and the subsequent efficient transfer from Th to Ho, it has become possible to efficiently operate Ho-doped lasers at room temperature. The room-temperature Cr,Tm,Ho (CTH) laser is practical enough for use outside of a laboratory environment.

The results of a first year of study showed that the CTH:YAG system was superior in terms of laser performance to CTH:YSGG and CTH:YSAG systems. Our second year concentrated on further characterization of the CTH:YAG laser.

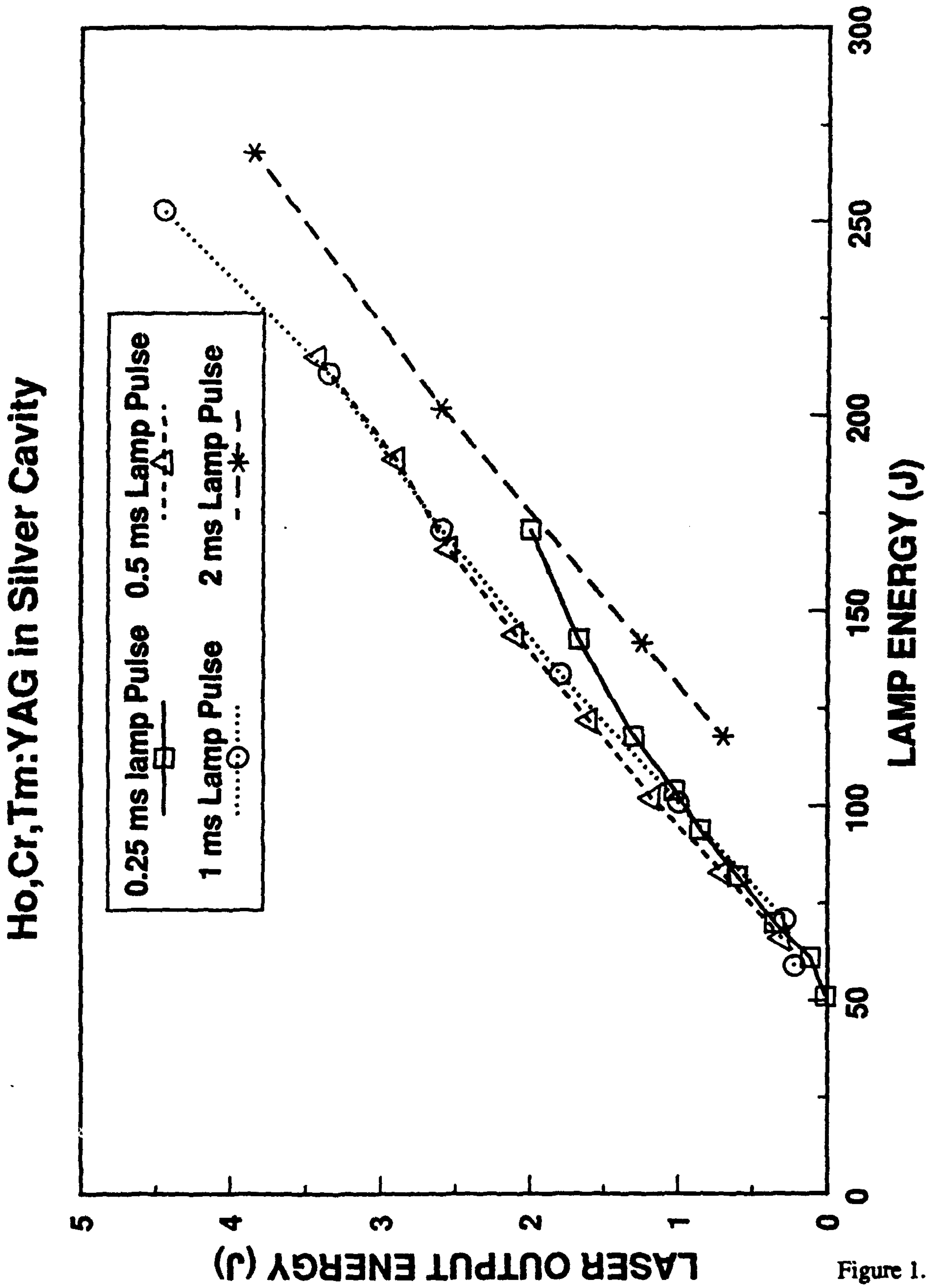
Figure 1 shows a series of input-output curves for a CTH:YAG laser pumped by our standard silver-ellipse pump cavity at a 2-Hz pulse rate, with pump pulsewidth as a parameter. The cooling-water temperature was set at 25 C and the output-mirror reflectivity was 90%. As is evident from the data, the performance of the CTH:YAG laser is nearly independent of pulsewidth, at low pump energies, for widths in the range 0.25-1 msec, while the apparent threshold for 1.5-msec pulses is higher. The slope efficiency with the longest pulsewidth is comparable to the shorter widths, however. The rolloff in energy for the 0.25-msec pulses may be due to a shift in the lamp peak emission to shorter wavelengths at high energies, with a subsequent reduction in slope efficiency. Similar input-output curves were observed in experiments in which we used a Spectralon-based diffuse pump cavity; these curves appear in Figure 2. A comparison of the input-output data for the two types of pump cavities appears in Figure 3, and shows that the use of the diffuse cavity resulted in only a slight reduction in performance.

The higher threshold for the 1.5-msec pump pulse is not expected from simple considerations of the ratio of pump pulsewidth to the holmium upper-state lifetime (7 msec), and may be an indication of cross-relaxation effects among holmium or holmium and thulium ions. Further investigation of this issue is planned.

We began an investigation of the Q-switched behavior of CTH:YAG by obtaining an AR-coated, fused-silica acousto-optic Q-switch for use at the holmium 2.1-μm wavelength. Our initial temporal data showed considerable multiple-pulse behavior, some of which may be due to inadequate hold-off of the Q-switch. We determined that the RF driver for the device was faulty, and sent the unit back for repairs. Further work on Q-switching will be done in the third year.

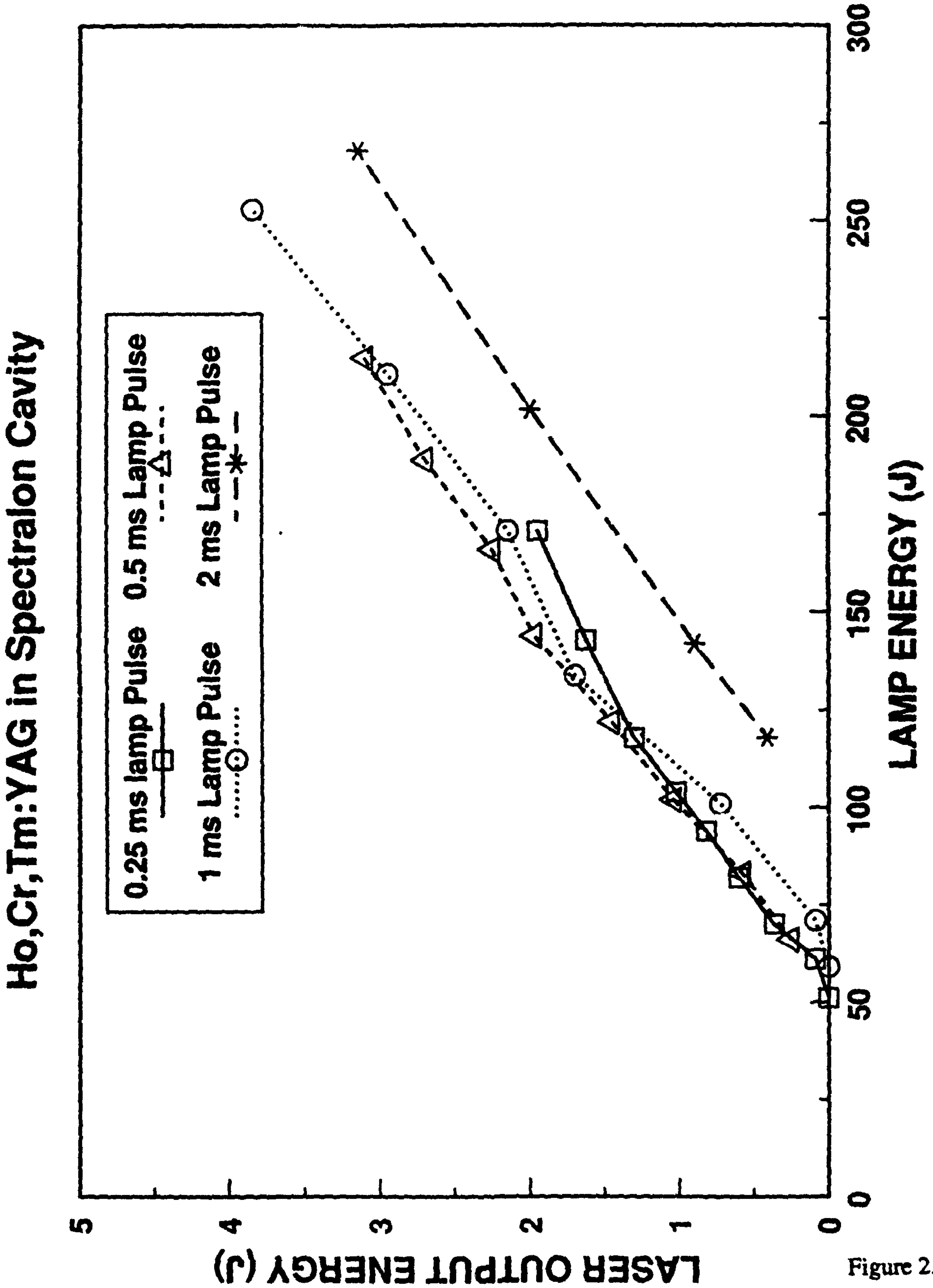
### 2.3 Erbium-doped lasers

The Phase I effort associated with this program concentrated on a study of erbium (Er) lasers, in particular, the Cr,Er:YSGG system, and the results have been published [3]. To date, we have limited our laser studies to the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition in Er, which yields laser output in



Ho,Cr,Tm:YAG in Silver Cavity
0.25 ms lamp Pulse
0.5 ms Lamp Pulse
1 ms Lamp Pulse
2 ms Lamp Pulse
LASER OUTPUT ENERGY (J)
LAMP ENERGY (J)
0
1
2
3
4
5
0
50
100
150
200
250
300


Figure 1.



Ho,Cr,Tm:YAG in Spectralon Cavity
0.25 ms lamp Pulse
0.5 ms Lamp Pulse
1 ms Lamp Pulse
2 ms Lamp Pulse
LAMP ENERGY (J)
LASER OUTPUT ENERGY (J)
0
50
100
150
200
250
300
0
1
2
3
4
5


Figure 2.

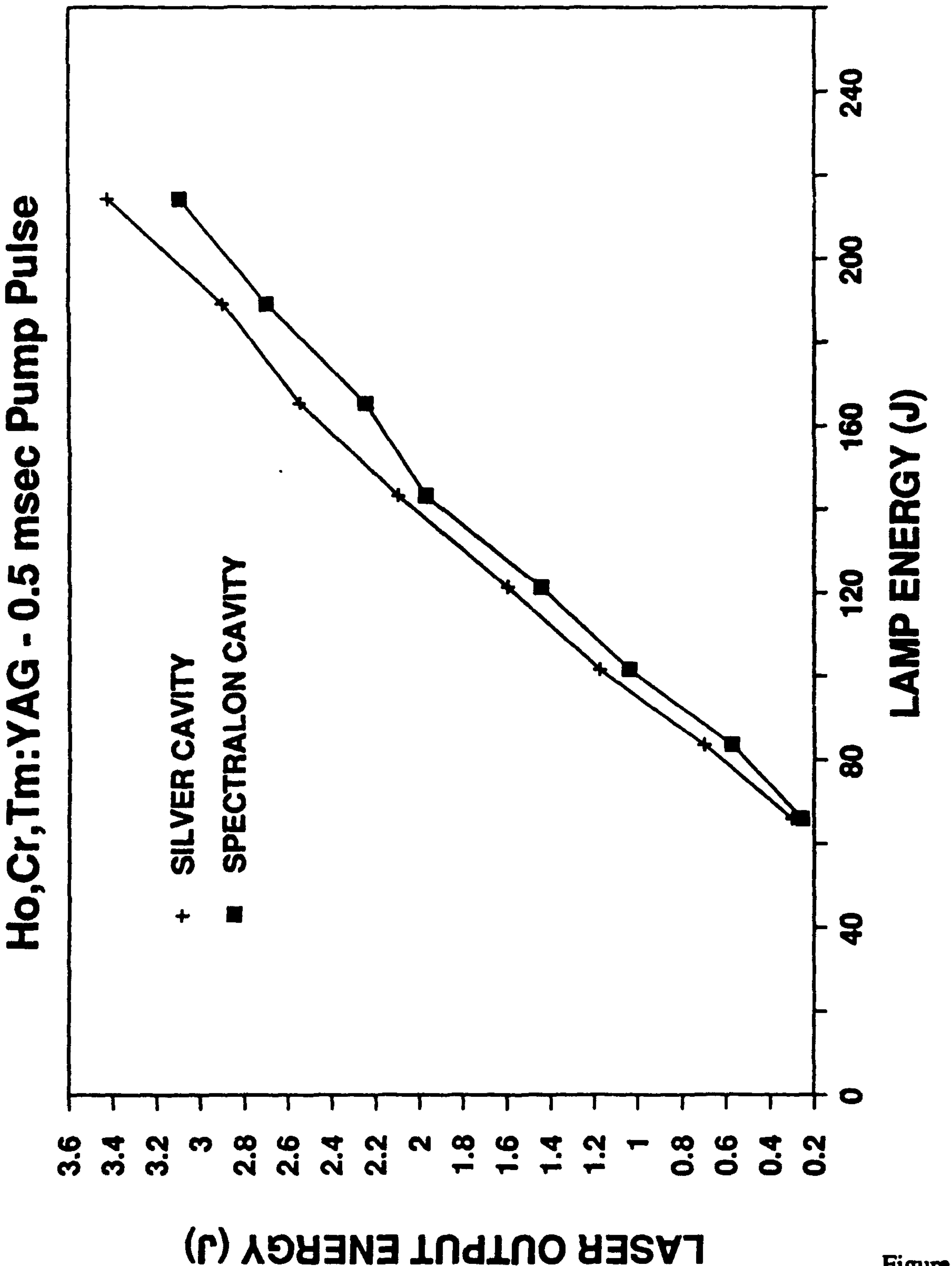
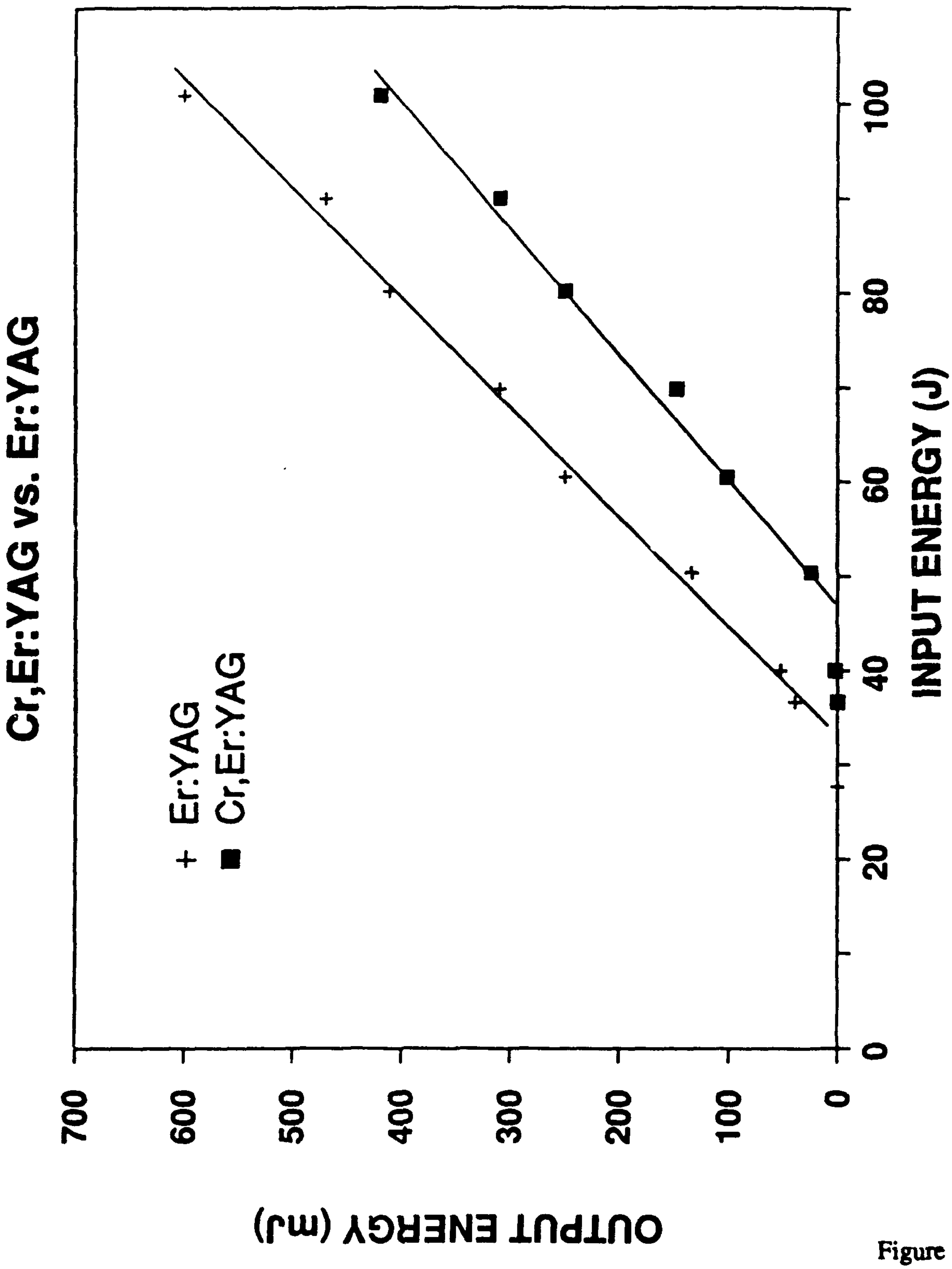

Ho,Cr,Tm:YAG - 0.5 msec Pump Pulse
+ SILVER CAVITY
■ SPECTRALON CAVITY
LASER OUTPUT ENERGY (J)
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
40
80
120
160
200
240
LAMP ENERGY (J)

Figure 3.

the 2.8-μm region and is of interest as a mid-IR source, a pump for infrared parametric oscillators and a source for laser surgery. In our Phase I work the spectroscopy of Cr,Er:YSGG was extensively examined, and in the Phase II work to date we have concentrated more on examining the laser characteristics of the material. In the first year of the Phase II research we studied techniques for improving the performance of Cr,Er:YSGG laser in terms of reduced threshold and increased slope efficiency and pulse repetition rate. We also compared the performance of Er:YAG with Cr,Er:YSGG and measured the level of thermal lensing in both materials.

Near the end of the first year we obtained a rod of Cr,Tm,Er:YSGG to determine whether the Tm ions would improve laser performance by aiding in the relaxation of the lower laser level. Preliminary experiments showed that the input-output performance with this material was similar to the Cr,Er:YSGG system. In the second year we used the variable-pulsewidth power supply to study the behavior of the Cr,Tm,Er:YSGG laser as a function of pump pulsewidth. Given that the long lifetime of the Er lower level tends to make operation with long pump pulses less efficient, due to filling of the lower level, we wanted to examine the effect of increased pulsewidth on output characteristics. We found that, in the pulsewidth range from 0.25-1 msec, the Cr,Tm,Er:YSGG laser threshold energy increased linearly with pulsewidth while the slope efficiency increased slightly, from 0.8% to 1.0%. An examination of the temporal output showed that relaxation oscillations continued throughout the pump pulse, with no evidence of pulse-power falloff even for a 1-msec pump. However, similar behavior was observed for Cr,Er:YSGG, and thus the effects of Tm in reducing lower-level buildup, if any, do not show up in the temporal behavior of the Er laser.

The effectiveness of Cr sensitization of rare earths is a function of the energy overlap between Cr emission and the rare-earth absorption, as well as the product of the dipole moments for the two processes. In general Cr sensitization is not effective in the YAG host crystal because the relatively high crystal field in YAG results in essentially all the Cr emission being from the narrow-linewidth, spin-forbidden $^2E \rightarrow {}^4T_2$ transition. It is hypothesized that the Cr-Tm transfer in the CTH:YAG laser is efficient only because of the near-perfect resonance between the Cr emission and one of the Tm absorption lines. There is no such resonance between the Cr emission in YAG and any of the Er lines, and thus we would expect that Cr,Er:YAG system would show little, if any improvement over the Er:YAG system. We were able to obtain, at low cost, a crystal of Cr,Er:YAG (2% Cr, 40% Er) to see if there might be some increase in slope efficiency. Figure 4 shows the input-output curve for a 5 mm×75 mm, Cr,Er:YAG crystal (30% Er, 1% Cr) compared to the same size 50% Er:YAG rod; the Cr-doped system showed slighly poorer performance, as expected.



Cr,Er:YAG vs. Er:YAG
+ Er:YAG
■ Cr,Er:YAG
OUTPUT ENERGY (mJ)
0
100
200
300
400
500
600
700
INPUT ENERGY (J)
0
20
40
60
80
100


Figure 4.

## 2.4 Thulium-doped lasers

The $^3F_4 \rightarrow ^3H_6$ laser transition of the thulium ion results in the generation of wavelengths around 2 μm. In many ways the Tm laser is similar to the Ho laser, both in wavelength and in the nature of the transition, which terminates on partially filled levels of the ion ground state. In general, the gain cross section for the 2-μm Tm laser transition is smaller than that of the Ho transition, and one expects that the laser threshold will be higher. One potential application for the Tm laser is in laser medicine, where the somewhat shorter wavelength of the Tm transition is more strongly absorbed by liquid water (and hence tissue) than that of the Ho laser.

We had initially considered that the Tm laser would not be worth investigating, for the following reason: for Cr→Tm transfer to be effective, a crystal must be doped with high levels of Tm, while for low-threshold operation at room temperature, the Tm doping level should be low to minimize the upper-state population required for net gain. However, we received reports of relatively good performance from Cr,Tm:YAG (CT:YAG) lasers at room temperature, based on experiments at Quantronix (Smithtown, NY) and at the Naval Research Laboratory (Leon Esterowitz, *et Al*), and were able to obtain two sample laser rods from Milan Kokta at Union Carbide for initial experiments.

Figure 5 presents a variety of input-output energy curves for different pump pulsewidths and for two different 6.3 mm×75 mm rods, labeled OJ72 and OJ73, operated with a silver-ellipse pump cavity at a 2-Hz pulse rate. Rods OJ72 and OJ73 were doped with 1% Cr, 2% Tm and 2% Cr, 1.5% Tm respectively, and had uncoated ends; the output-mirror reflectivity was 90%. One striking feature of the data is the high threshold energies observed in all cases, about twice those observed for CTH:YAG systems with comparably sized laser rods. The rod with higher Tm concentration showed slightly better performance, and the best slope efficiencies were slightly over 1%. Temporal measurements of the laser output indicated that near threshold, with a 0.5-msec pump pulse, the laser output did not occur until 0.35 msec after the pump pulse was over, and indication that a major portion of the upper-level excitation was the result of an indirect pumping process, likely the cross relaxation of two excited Tm ions. The Tm-laser output was observed to appear at two wavelengths, 2.0048 and 2.0088 μm, with the latter wavelength appearing later in the pulse.

Given that the CT:YAG laser performance improved with increased Tm concentration, we were encouraged to try higher levels of Tm doping. In a related issue, the NRL group reported [4] that performance of the CTH:YAG laser was improved if the Cr concentration was lower than 1%, and thus we were also encouraged to try CT:YAG with lower Cr concentrations then before. Figure 6 shows the input-output curves for an AR-coated 6.3 mm×100 mm CT:YAG rod

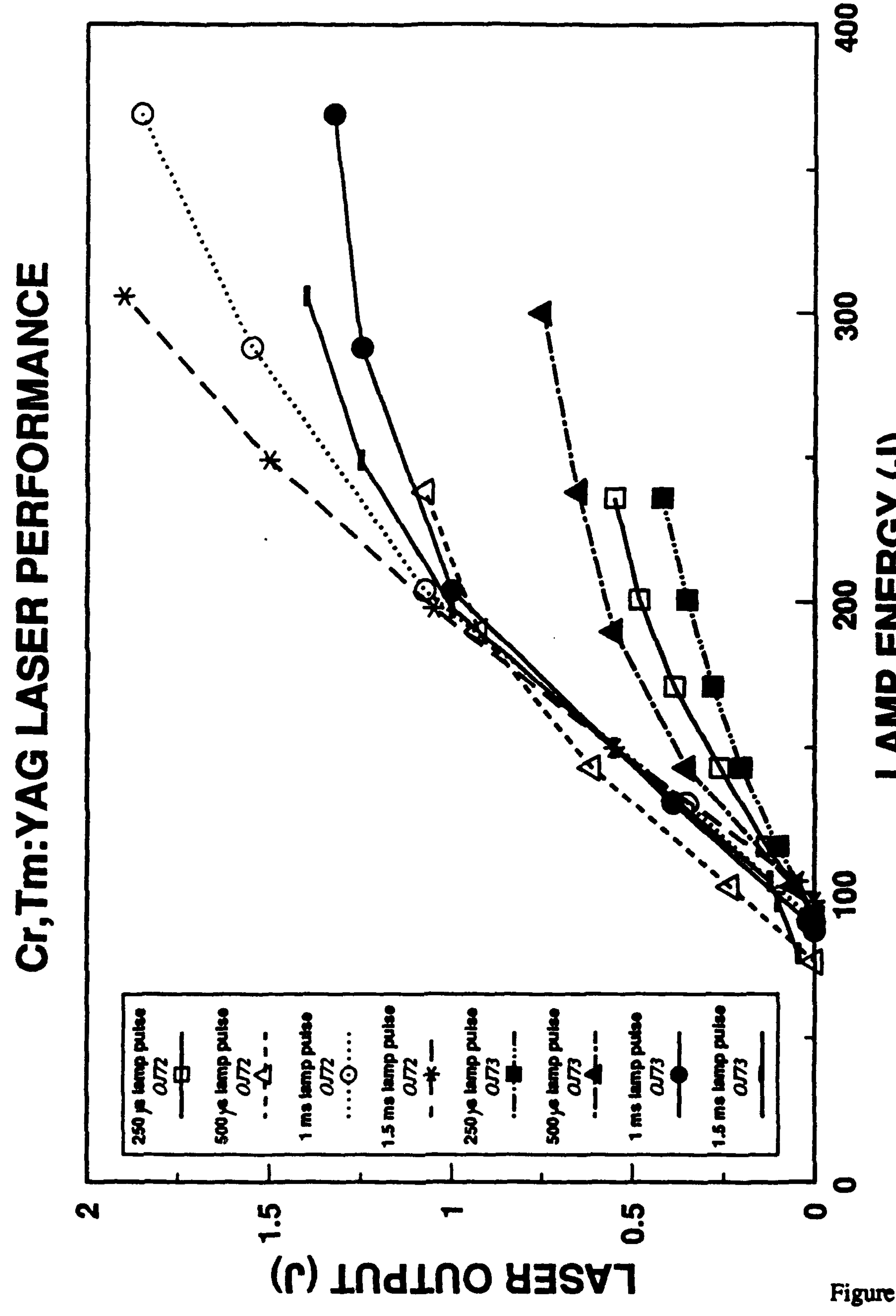
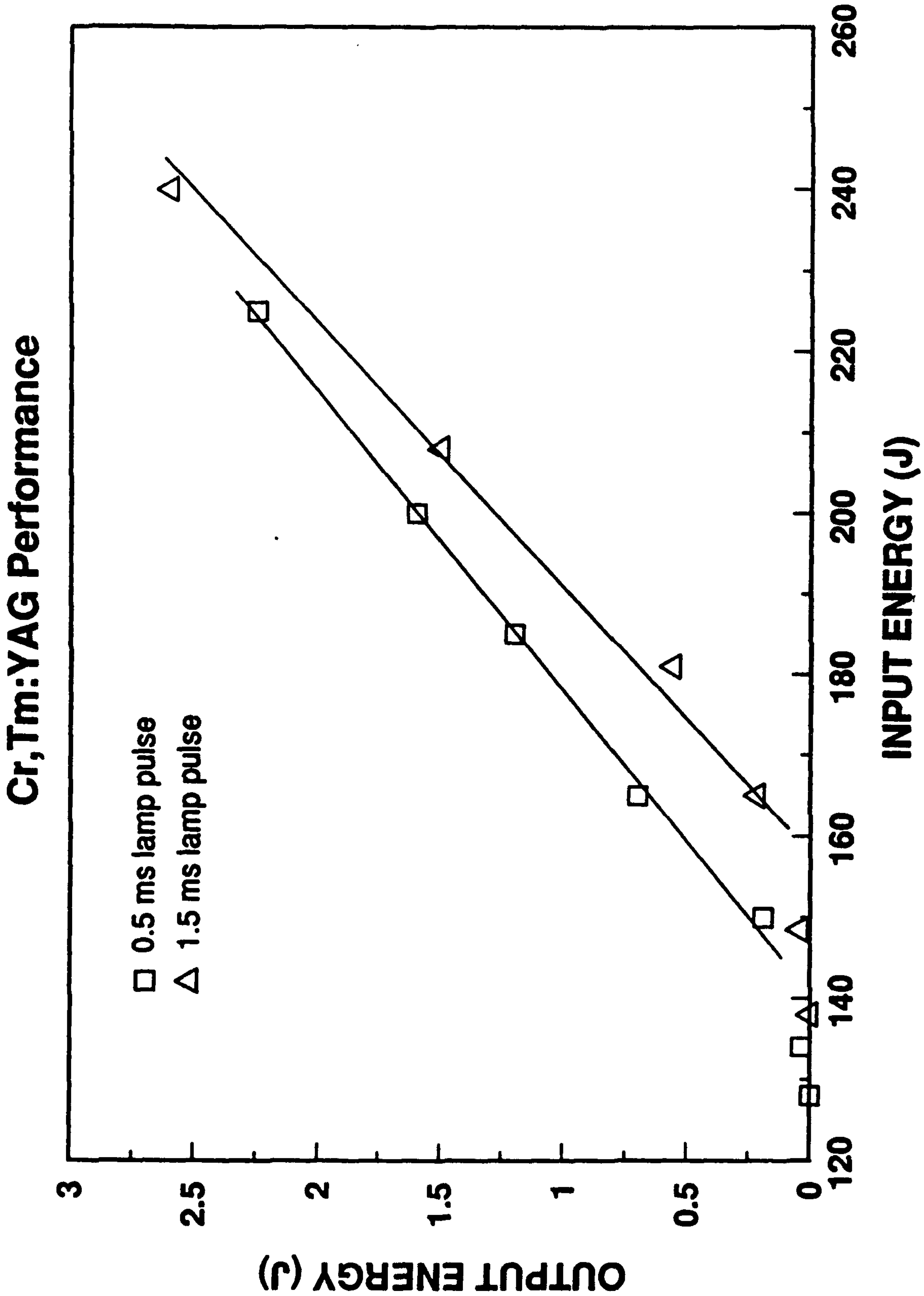

Cr,Tm:YAG LASER PERFORMANCE
LASER OUTPUT (J)
LAMP ENERGY (J)
0
0.5
1
1.5
2
0
100
200
300
400
250 μs lamp pulse OJ72
500 μs lamp pulse OJ72
1 ms lamp pulse OJ72
1.5 ms lamp pulse OJ72
250 μs lamp pulse OJ73
500 μs lamp pulse OJ73
1 ms lamp pulse OJ73
1.5 ms lamp pulse OJ73

Figure 5.



Cr,Tm:YAG Performance
0.5 ms lamp pulse
1.5 ms lamp pulse
OUTPUT ENERGY (J)
INPUT ENERGY (J)
0
0.5
1
1.5
2
2.5
3
120
140
160
180
200
220
240
260


Figure 6.

operated with a 90% output coupler, at a 2-Hz pulse rate. The threshold was higher than observed with the lower-Tm-doped material, but that may be due in part to the longer rod length, as systems with appreciable lower-level population tend to have a threshold that increases with rod size. The slope efficiency showed a significant increase, to 2.5% with a 1.5-msec pump pulse.

We plan to conduct more studies of the CT:YAG system in the third year, including measurements of the thermal lensing in rods with different levels of doping and more detailed studies of the laser temporal behavior.

### 2.5 Cr,Nd:GSGG slab laser

As the report for the first year noted, thermal lensing in the Cr sensitized laser materials we have studied is significant and, in a practical sense, complicates the design and operation of laser systems. Thermal effects can limit the amount of output available in a diffraction-limited beam. Another thermal effect that we have yet to study is that of stress-induced birefringence, resulting from the radial thermal gradients in the laser rod. The birefringence can dramatically limit the amount of linearly polarized output available, especially at high pump levels. Given that many applications, such as the pumping of parametric oscillators and coherent lidar, require both diffraction-limited and linearly polarized beams, we can anticipate problems with operation of conventional Cr-sensitized rod-geometry systems.

One solution to the problems of rod systems is the use of the total-internal-reflection, face-pumped slab geometry, which can minimize the effects of both thermal lensing and birefringence. The application of the slab geometry to Cr-sensitized materials would be the next logical step in laser development. We were able to obtain a slab-geometry system that had been initially built as part of a Navy (China Lake)-sponsored program. The active laser material was Cr,Nd:GSGG, similar in thermal characteristics to the garnet crystals studied in this program. We set up a number of different experiments to characterize the operation of the Cr,Nd:GSGG slab system, and in doing so established a number of new levels of performance for Cr-sensitized garnet lasers. We plan to use our experimental experience and results as the basis for extending operation of slab lasers to CTH:YAG and, possibly Cr,Er:YSGG systems. The results of our slab-laser studies are summarized in a paper to be published as part of the proceedings of the OSA Topical Meeting on Advanced Solid State Lasers, and we include the paper as Appendix A of this report.

### 2.6 $Cr^{4+}$ ions in GGG

Recently, tunable laser action around 1235 nm from Cr in forsterite ($Mg_2SiO_4$) has been attributed to $Cr^{4+}$ ions [5]. It is possible $Cr^{4+}$ ions can also be present in garnet crystals such as

GGG if the crystals are also doped with divalent metal ions such as $Ca^{2+}$ or $Mg^{2+}$. We began an investigation into the possibility of laser action in $Cr^{4+}$:GGG by ordering samples of the crystals in the first year of the contract, and in the second year we measured a number of the spectroscopic properties of the materials. Our attempts to obtain laser action have been unsuccessful to date, however, possibly because of the poor optical quality of the material.

Our spectroscopic measurements included absorption spectra on a number of polished samples, as measured by a Perkin-Elmer Lambda 9 absorption spectrophotometer. Data was taken with the samples at room temperature and, with the aid of a small Dewar, with samples at 77 K. The low-temperature data allowed the identification an apparent zero-phonon line in the wavelength region around 1100 nm. Figure 7 shows the absorption from several slices of one crystal over the wavelength region from 300-900 nm. We concluded from the data that the samples had a considerable level of $Cr^{3+}$ ions and attempted to subtract the absorption from those centers by using absorption data from GGG crystals which contained only $Cr^{3+}$. Figure 8 shows the "corrected" absorption data, where the absorption is presumably due to centers other than $Cr^{3+}$. Whether the remaining absorption is due only to $Cr^{4+}$ centers is a matter for further study. We do suspect that the weak absorption present around 1 μm, shown in Figure 9 for a sample at 77 K, is the result of $Cr^{4+}$, given the similarity of the data to that for forsterite [5]. A zero-phonon line is apparent at 1130 nm. We used a pulsed, 1.05 μm Nd:YLF laser to excite fluorescence from the samples, and the resultant fluorescence in the 1400-nm region is plotted in Figure 10, for samples at 77 and 300 K. The absence of a corresponding zero-phonon line at 1130 nm in emission is one puzzling aspect of the fluorescence data. The fluorescence 1/e lifetime was observed to be 1.8 μs at room temperature, and was fit well by a single exponential model; the lifetime was found to be the same for a number of different samples. At dry-ice and liquid-nitrogen temperatures the 1/e times were measured to be 7 and 16 μsec, respectively, but the decay was not well characterized by a single exponential model after two e-folding times.

We attempted to observe laser action from a polished but uncoated Cr:GGG crystal, placed between two cavity mirrors and optically pumped by a Q-switched Nd:YLF laser. No lasing was observed up to the damage level of the Cr:GGG crystal surface. Further investigations of this material will be carried out in the third year.

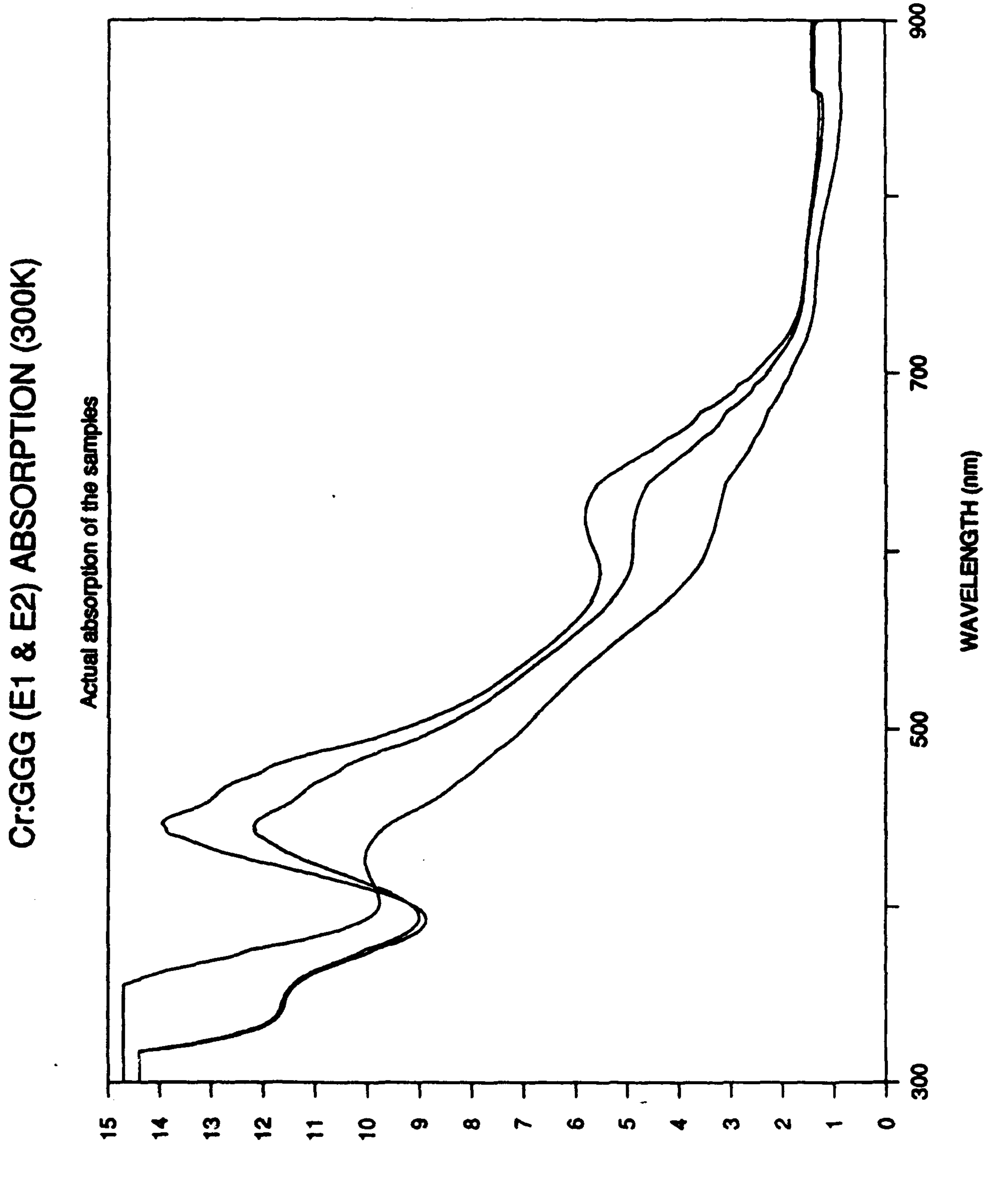

Cr:GGG (E1 & E2) ABSORPTION (300K)
Actual absorption of the samples
ABSORPTION COEFFICIENT (cm-1)
WAVELENGTH (nm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
300
500
700
900

Figure 7.

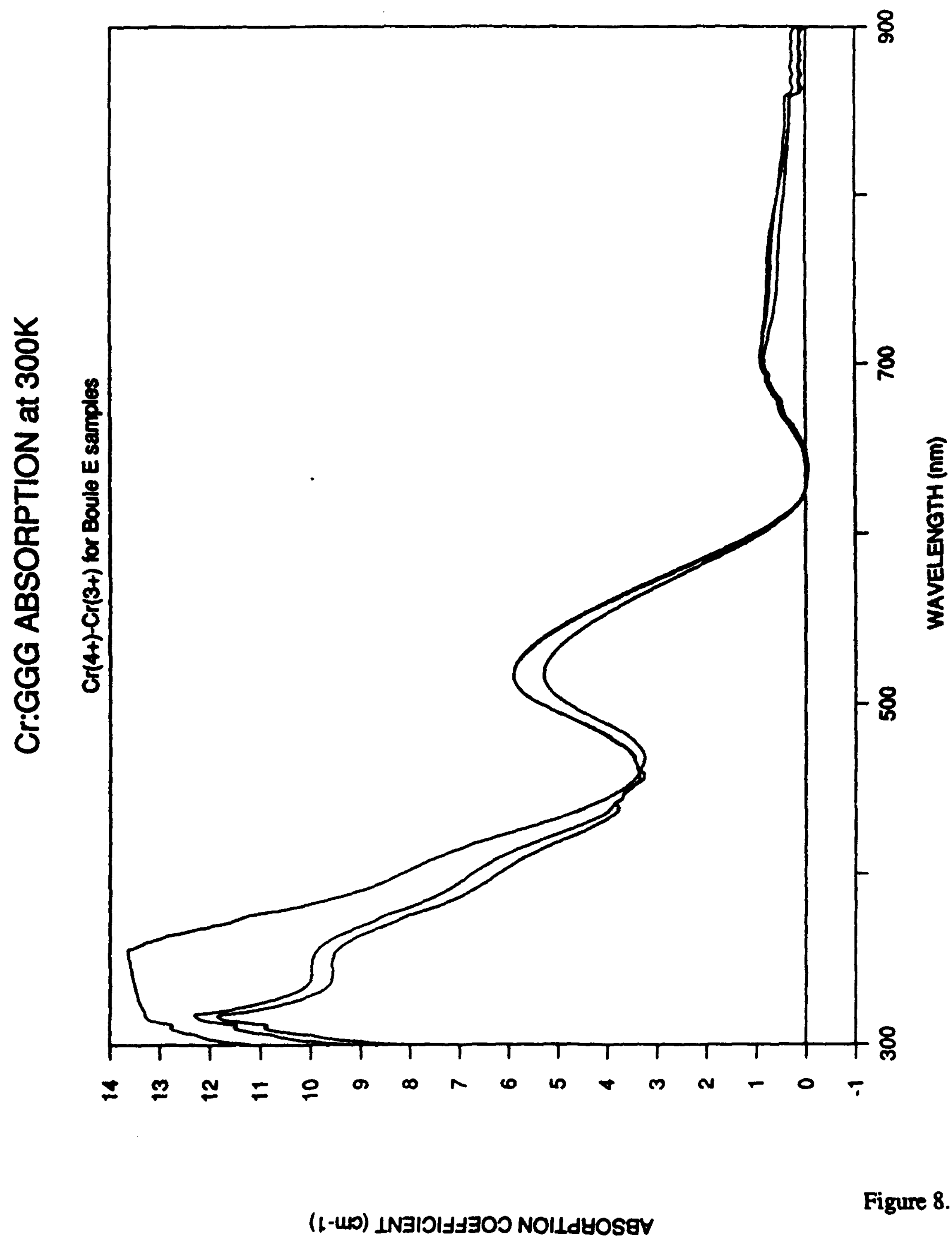

Cr:GGG ABSORPTION at 300K
Cr(4+)-Cr(3+) for Boule E samples
WAVELENGTH (nm)
ABSORPTION COEFFICIENT (cm-1)
300
500
700
900
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1

Figure 8.

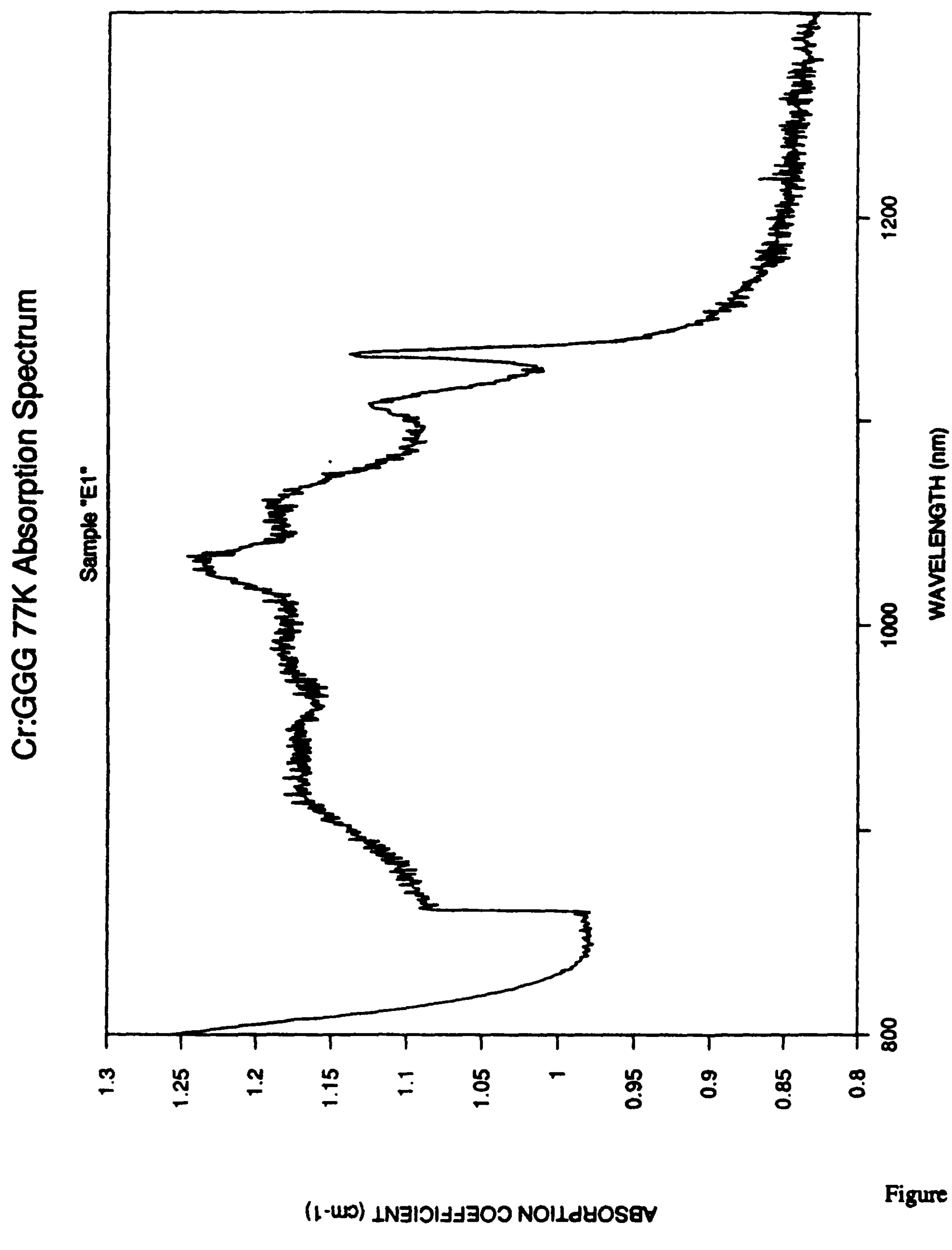

Cr:GGG 77K Absorption Spectrum
Sample "E1"
ABSORPTION COEFFICIENT (cm-1)
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
800
1000
1200
WAVELENGTH (nm)

Figure 9.

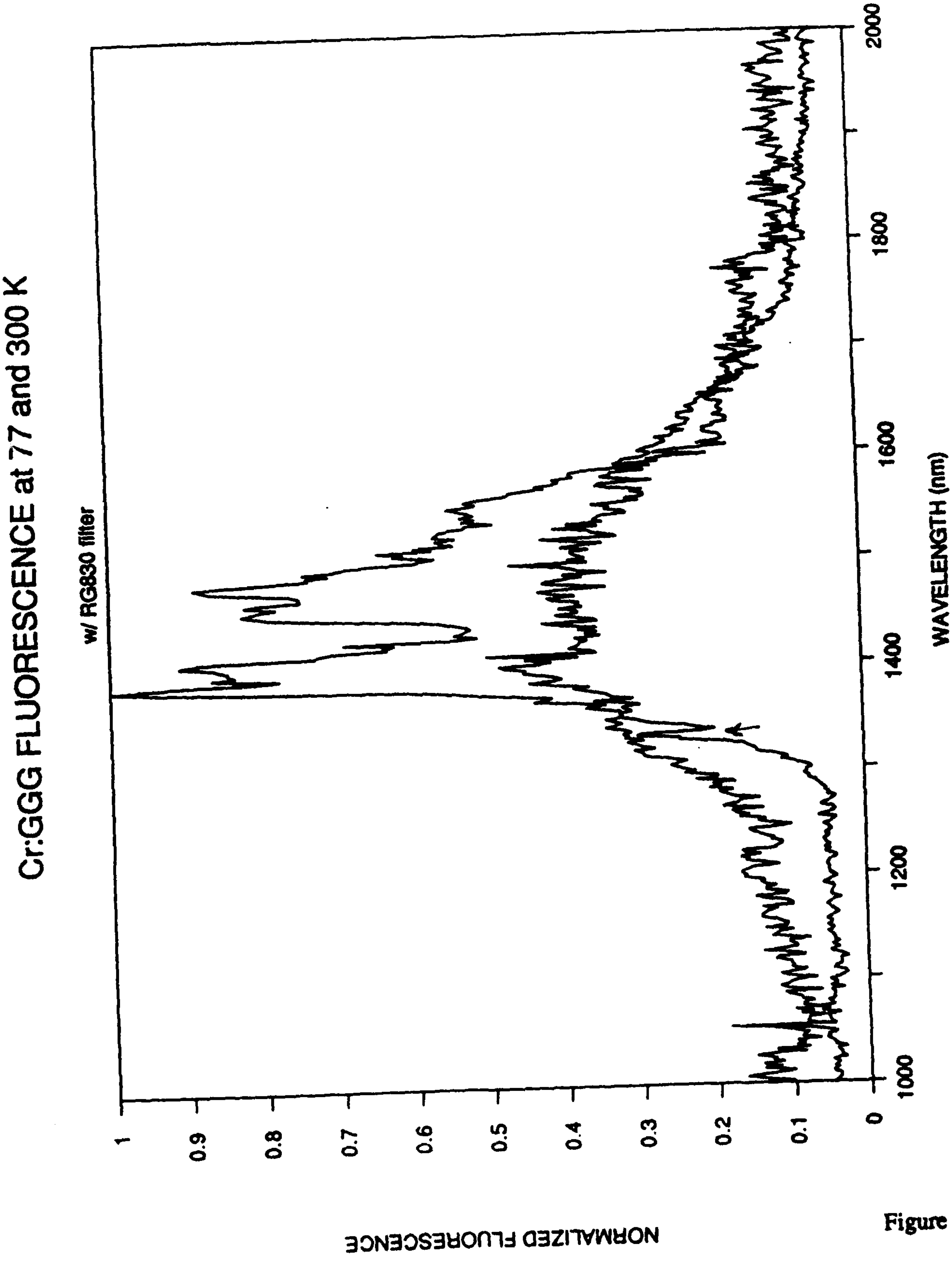

Cr:GGG FLUORESCENCE at 77 and 300 K
w/ RG830 filter
NORMALIZED FLUORESCENCE
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1000
1200
1400
1600
1800
2000
WAVELENGTH (nm)

Figure 10.

### 2.7 References


[1]. J.P. Markiewicz and J.L. Emmett, IEEE J. Quantum Electron. QE-2, 707 (1966).

[2]. B.M. Antipenko, A.S. Glebov, T.I. Kiseleva and V.A. Pis'mennyi, Sov. Tech. Phys. Lett. **11**, 284 (1985).

[3]. A.N. Alpat'ev, E.V. Zharikov, S.P. Kalitim, A.F. Umyskov and I.A. Shcherbakov, Sov. J. Quantum Electron. **17**, 587 (1987).

[3]. P.F. Moulton, J.G. Manni and G.A. Rines, IEEE J. Quantum Electron. **24**, 960 (1988).

[4]. G.J. Quarles, A. Rosenbaum, C.L. Marquardt and L. Esterowitz, Appl. Phys. Lett. **55**, 1062 (1989).

[5]. V. Petricevic, S.K. Gayen and R.R. Alfano, Appl. Phys. Lett. **53**, 2590 (1988).


## 3 Publications

We have not published any journal articles in the second year of the effort. Our intention is to publish several comprehensive articles near or immediately after the end of the contract work.

## 4 Personnel

The following personnel have worked on the program:

Peter F. Moulton, Principal Investigator, Ph.D. in Electrical Engineering from M.I.T., 1975
Glen Rines, Laser Physicist, B.A. Gordon College, Physics, 1977
David Rines, Electro-Optics Assistant, B.S. Gordon College, Physics and Mathematics, 1988.
David Welford, Laser Physicist, Ph.D. Imperial College of Science and Technology, 1980.

## 5 Interactions

Results of the research on the average-power and thermal-lensing properties of Er and Ho lasers were presented as Poster Paper WF8 at CLEO'89, April 24-28, Baltimore. The authors were David Rines, Peter Moulton and Jeff Manni. An abstract of the paper is included as Appendix B. Results of the research on the Cr,Nd:GSGG slab laser were presented as oral papers by David Rines at the OSA Topical Meeting on Advanced Solid State Lasers, in Salt Lake City, March 5-7, 1990 (Paper WF1), and at CLEO '90, Anaheim, May 21-25 (Paper CTUJ2). As in the first year, the results of some of these studies have been used in the further development of an SEO commercial product, the ***Laser 1-2-3***, particularly in the applications related to laser medicine and coherent lidar.

## Appendix A: Paper submitted to ASSL '90

# Efficient Operation of a Nd,Cr:GSGG Slab Laser

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The total-internal-reflection, face-pumped solid state laser (or, simply, the slab laser) has been under development for nearly two decades, since it was first demonstrated by Chernoch and Martin at General Electric [1]. Much of the development has concentrated on the demonstration of systems with near-diffraction-limited performance, which in principal is more readily achieved with the slab laser than with conventional rod-geometry configurations. As Danilov *et al* have pointed out [2], most of the slab lasers described to date have had considerably lower efficiencies than rod lasers, often the result of pumping-cavity designs chosen for a high uniformity of illumination over the slab surface.

In this paper we describe a high-efficiency slab Nd,Cr:GSGG laser system that has essentially the same efficiency as a rod-geometry laser. The device, not designed for the ultimate in mode quality, nevertheless shows significant reduction in beam divergence in both dimensions and, more importantly, operates without the problems of thermally induced birefringence that limit the performance of rod lasers [3]. As a result, Q-switched operation with conventional polarization switches has been demonstrated at high average powers.

The laser head utilized a Nd,Cr:GSGG slab of dimensions 5×8×93 mm, doped with $2\times10^{20}$ $cm^{-3}$ Nd and Cr and cut for in-line operation with Brewster-angle ends. The double-ellipse, flooded pump cavity employed silvered reflecting surfaces and two 63.5-mm-discharge-length xenon arc lamps on either side of the slab, with samarium filters between the lamps and slab. The slab reflecting surfaces were coated with a deposited film designed both to reduce the effects of parasitic oscillations and to protect the surfaces from contaminants in the cooling fluid.

Initial tests of the system were carried out at Litton Laser Systems [4]. In these experiments long fused silica prisms were mounted on the edges (i.e. unpolished surfaces) of the slab in an attempt both to increase the pump coupling efficiency and to suppress the heat flow through these surfaces. The cooling fluid was a glycol/water mixture. The series-connected lamps were driven by a conventional LC discharge network, with a 20-μF capacitor and an ≈10 μH inductor. Figure 1 shows the 10-Hz normal mode performance of the laser at 1061 nm, obtained with the use of an optical cavity consisting of a 50%-reflectivity flat mirror and a 10-m-radius concave high-reflector mirror spaced 25-cm apart. The slope efficiency of 7.5% and overall efficiency of 5.9% at 1.2 J of output compare favorably with rod-laser data showing slope efficiencies in the 6-7% range [5,6].

The remainder of the data discussed here were taken at Schwartz Electro-Optics, where the flashlamps were driven by a transistor-switched power supply, capable of producing nearly rectangular-shaped drive pulses with continuously variable duration over the range 0.1-1 msec. The normal-mode slope efficiency was found to be almost invariant with lamp pulsewidth in that range, from a low of 4.2% at 0.1 msec to a high of 4.6% at 1 msec. At the longest pulsewidth we generated

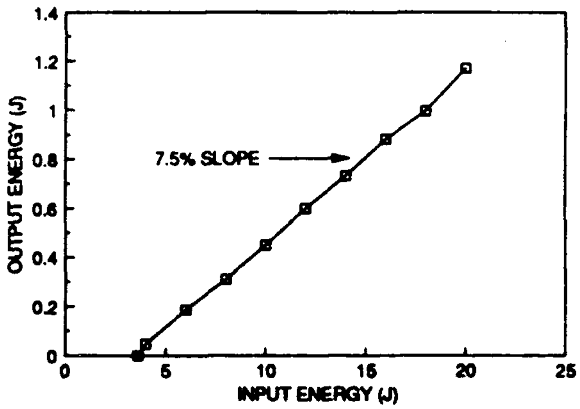


Figure 1. Normal-mode input-output curve for Nd,Cr:GSGG slab laser at 10-Hz pulse repetition rate.

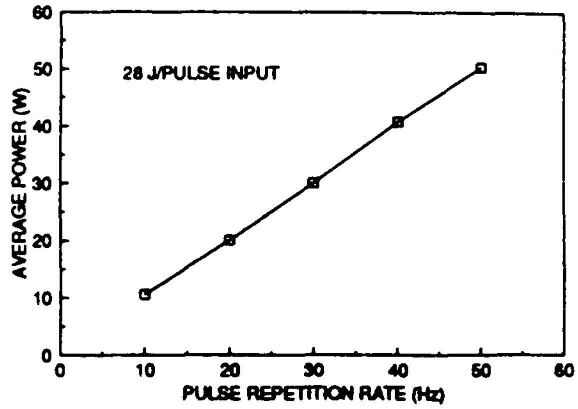


Figure 2. Normal-mode average power output vs. pulse repetition rate.

2.2 J of energy with 60 J total energy input at a 10-Hz pulse repetition rate. In all experiments performed at SEO higher energies than discussed here were not attempted for fear of damage to the slab. We were not able to generate efficiencies as high as those observed in the initial tests, possibly because of aging in the flashlamps, the pump-cavity coating and the slab coating. Other possibilities include the absence of the prisms and the cooling fluid being water without glycol.

In Figure 2 we show the normal-mode average power output of the system as a function of pulse repetition rate, for a fixed lamp energy of 28 J/pulse in a 0.25-msec pulse. The cavity was comprised of a 5m-radius concave HR mirror and a flat 50%R output mirror spaced 30 cm apart with the slab centered between them. Up to 50 W of average power was generated at 50 Hz with an overall efficiency of 3.6%. The linear nature of the data as plotted indicates negligible thermally induced birefringence.

In rod lasers when a linear polarizer is placed in the cavity there is significant loss at high average powers due to *radially*-dependent thermally-induced birefringence. In a slab laser the main axes of the birefringence are oriented parallel and perpendicular to the slab polished surfaces. Therefore, a beam polarized along one of these axes can propagate without being depolarized. At the 50 W level the degree of beam polarization was found to be high, at least 100:1.

Operation of the slab laser at 1310 nm was also investigated. The laser cavity employed a 2-m-radius concave high reflector and a flat, 80%-reflectivity output coupler. With 0.25-msec pump pulses at 10 Hz we observed a slope efficiency of 2.2%, with a maximum energy of 1.1 J; at 50 Hz the laser generated 13.6 W of average power.

We added a KD*P electro-optic Q-switch and a "pile of plates" polarizer to the laser cavity for 1061-nm Q-switching experiments. The cavity mirror spacing was increased to 56 cm and the output-mirror reflectivity was reduced to 20%. The pump pulsewidth was set to 150μs to avoid losses due to fluorescence. With the addition of the Q-switching optics the laser slope efficiency was somewhat lower. Figure 3 plots energy input-output at a 50 Hz pulse repetition rate for both normal-mode and Q-switched conditions, showing that the stored energy in the slab was efficiently extracted in Q-switching and that parasitic effects were minimal up to the maximum output of 364 mJ/pulse. The Q-switched pulsewidth at the highest energy outputs was approximately 20 nsec. Again, we did not attempt to operate at higher energies because of a concern that the cavity optics or the slab might be damaged.

We carried out preliminary experiments to frequency double the output of the Q-switched laser, using a temperature-tuned CD*A crystal inserted directly on the output beam, without any focusing or beam-shaping optics. Up to 130 mJ/pulse of second-harmonic energy was generated for 380 mJ/pulse of input at a 25-Hz pulse repetition rate, for a conversion efficiency of 35%. At higher pulse repetition rates the conversion efficiency was reduced, due presumably to an increased beam divergence from the slab laser.

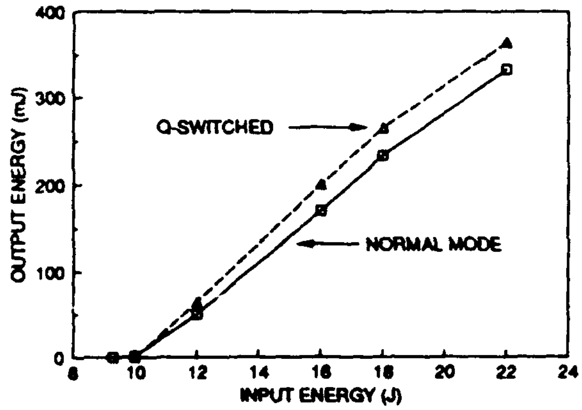


Figure 3. Q-switched and normal-mode output energies vs. pump input energy at a 50-Hz pulse repetition rate.

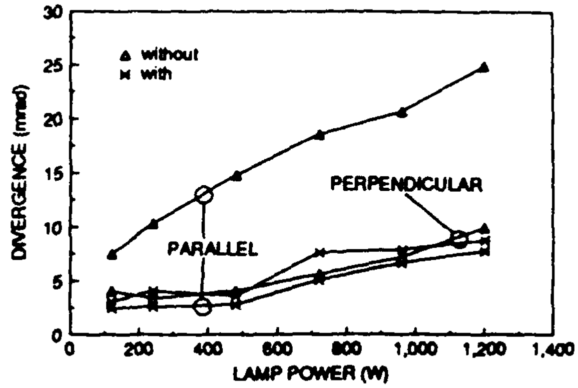


Figure 4. Divergence of Nd,Cr:GSGG slab laser as a function of lamp average power in directions perpendicular and parallel to slab polished faces with and without Sylgard.

The slab-laser beam divergence was measured by observation of patterns on burn paper. As expected, the divergence in the direction normal to the slab polished surfaces was low, and a weak function of pump average power, while divergence in the other direction was high. We used a CW, 1150-nm He-Ne laser to probe the slab optical properties under pumping conditions and observed a positive cylindrical thermal lens, ranging from 120 cm focal length at 400 W of average pump power to 33 cm at 1200 W. The 1061 nm beam divergence resulting from this lens is represented by the dashed lines in Figure 4.

As reported by Kane *et al.* [3] the use of an insulating layer of silicone elastomer is effective in reducing heat flow in the direction parallel to the slab polished surfaces. We applied a thin layer (≈1mm thick) of Dow Corning Sylgard 186 to the unpolished surfaces of the slab. This resulted in a dramatic decrease in beam divergence in the direction parallel to the slab polished surfaces, and little or no change in that of the other direction. The solid line in Figure 4 represents the resulting beam divergence in each direction.


**Acknowledgements:**

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References:


1. J. P. Chernoch and W. S. Martin, "Multiple internal reflection face-pumped laser," U.S. Patent 3,633,126, 1972

2. A.A. Danilov *et al.*, Sov. J. Quantum Electron. 19, 17 (1989).

3. The advantages of the slab geometry in eliminating birefringence have been discussed previously by T.J. Kane, R.C. Eckardt and R.L. Byer, IEEE J. Quantum Electron QE-19, 1351 (1983).

4. M. A. Acharaker, D.P. McCarthy, D.A. Dobberpuhl and H. W. Willhite, in *Proceedings of Boulder Damage Symposium*, (Department of Commerce) November, 1988 (in print).

5. P.F. Moulton, Solid State Research, Quarterly Technical Report, 1984:3, M.I.T. Lincoln Laboratory, Lexington, MA.

6. J.A. Caird *et al*, Appl. Opt. 25, 4294 (1986).

## Appendix B: CLEO '89 Paper

### Average-Power Performance of Chromium-Sensitized Mid-Infrared Lasers

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Mid-infrared lasers in the 2.1- and 2.8-μm wavelength regions based, respectively, on holmium (Ho)-doped and erbium (Er)-doped crystals have existed for two decades. Until recently, both the Ho- and Er-lasers had considerable disadvantages when compared with 1.06-μm neodymium-doped systems. The use of chromium (Cr) sensitization and a judicious choice of doping levels and host crystals [1-3] has resulted in a significant improvement in both Ho- and Er-doped room-temperature lasers. In this paper we report experimental results on the average-power performance of chromium-sensitized Ho and Er lasers.

We have examined two Ho-doped systems, Ho,Tm,Cr:YSGG and Ho,Tm,Cr:YAG. The thulium (Tm) ions provide an intermediate step in the transfer of excitation between Cr and Ho. Thresholds for laser operation in the YSGG host and the YAG host, for the same size (5 x 75 mm) rods with roughly comparable doping levels, were found to be almost equal, around 45 J with 200-μs-long lamp pulses. The YAG-based system to date has exhibited higher slope efficiencies, up to 3.6%, compared to around 2% for YSGG. In addition, the superior thermo-optical properties of YAG have allowed higher average-power operation. The YSGG-based laser has generated 9 W of power at a 3-Hz rate, while the YAG system has produced 15 W of output at 4 Hz. At rates higher than about 5 Hz the available average power drops, and the YAG laser has been capable, to date, of 6 W at 10 Hz.

Efficient operation of the Ho-doped lasers at high rates is limited, in part, by a strong thermal lensing established in the laser rod. We have measured the focal length of both YSGG and YAG rods by use of a 1.15-µm HeNe probe laser. At 400 W of average-power input the YSGG focal length is approximately 30 cm; in YAG the same focal length occurs at 800 W.

The highest average power output we have observed to date at 2.8-µm from the Er,Cr:YSGG laser has been 6.8 W at 10 Hz, using a 5 x 75-mm rod, with an overall efficiency of 1.3%. In contrast, an Er:YAG laser with a 6.25 x 100-mm rod has generated 11.8 W at 6 Hz. The major advantage of the YSGG system is the considerably lower threshold compared to Er:YAG. While YAG thresholds are typically in the region of 30-40 J, we have observed thresholds as low as 1.4 J for the 2.8-µm Er,Cr:YSGG laser when using 5 x 75-mm rods, 100-µs pump pulsewidths and a low-transmission (3%) output coupler. Such a low threshold has allowed near-threshold, power-supply-limited operation up to a 160-Hz repetition rate, with pulse output energies of approximately 1 mJ. In more practical systems, with 10%-transmission couplers, operation at 50 Hz with 4 W of average power and at 100 Hz with 1.25 W of power has been observed. In both cases the power-supply limitations prevented generation of higher power levels.

We are currently examining the performance of Er,Tm,Cr:YSGG lasers, in which the Tm ions may help depopulate the Er laser lower level and improve the system performance.

**References:**

1. B. M. Antipenko *et al.*, Sov. Tech. Phys. Lett. **11**, 284 (1985).

2. A.N. Allat'ev *et al.*, Sov. J. Quantum Electron. **16**, 1404 (1986).

3. E.V. Zharikov *et al.*, Sov. J. Quantum Electron. **16**, 635 (1986).